An Alternative Flight Software Trigger Paradigm

Kelly Smith, Robert Gay, Susan Stachowiak
NASA Johnson Space Center

AIAA GN&C, August 19-22, 2013, Boston, MA

Introduction

- Orion is scheduled to fly an orbital test flight, Exploration Flight Test-1 (EFT-1), in late 2014
- Mission Profile:
  - Launch from Kennedy Space Center aboard Delta-IV Heavy into LEO parking orbit
  - After 1 orbit, Delta IV-H upper stage injects the vehicle into an elliptical orbit which intersects the Earth
  - Orion flies high-speed guided entry, splashes down in Pacific Ocean west of Mexico

Introduction, cont.

- Once high-speed entry is complete, the vehicle must begin a parachute deployment sequence (PDS).
  - Jettison Forward Bay Cover (FBC)
  - Deploy Drogue Parachutes
  - Deploy Main Parachutes

Flight Software Triggers

- Typically, triggers are normally simple checks against thresholds:

```
if (altitude <= 24000)
   deploy_parachute();
```

- When required, additional conditions are added to increase the specificity of the trigger:

```
if (altitude <= 24000 && gps_is_available)
   deploy_parachute();
```

- When adding new conditions, the number of additional code paths increases, increasing code complexity.
- Code complexity increases software testing costs.
- Therefore, to minimize costs, simple flight software triggers are desired.

Motivation

- By design, deploy drogue parachutes no lower than 24,000 feet altitude, using GPS.

- If both GPS and the backup barometric altimeters are unavailable, then the navigated altitude may have large errors.

Motivation, cont.

- If PDS is still triggered based on navigated altitude in this scenario, many cases deploy too low or too high.

- An alternative trigger must be developed which uses a less error-prone signal.

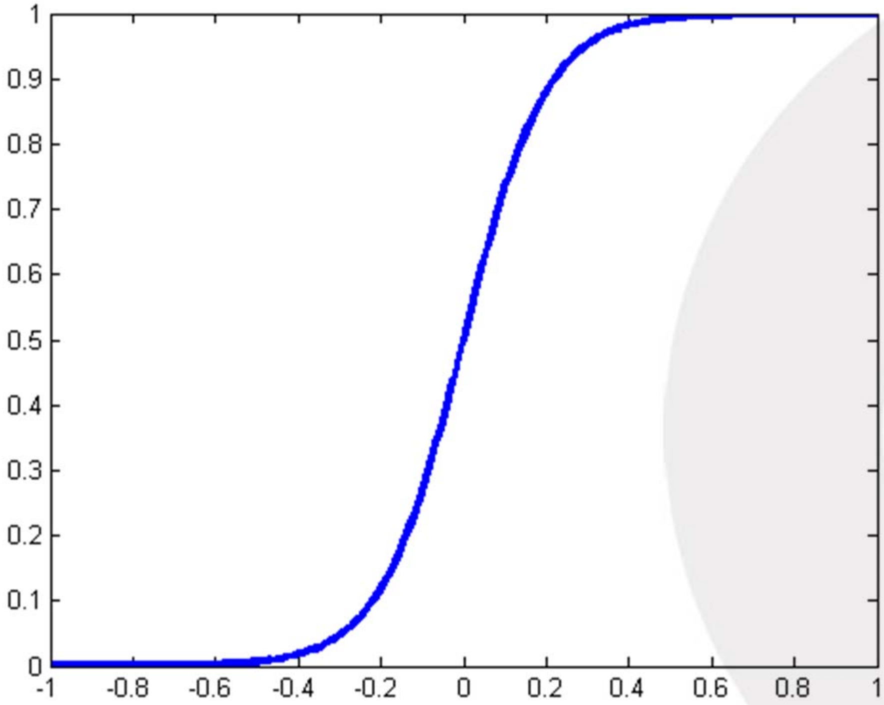
Introduction to Logistic Regression

- A statistical technique used for fitting a curve to classify data into separate classes.

- Simplest version is binary logistic regression (2 classes of data)

- Fit a logistic function, also known as a sigmoid function (S-curve), to these two classes of data

Logistic Function

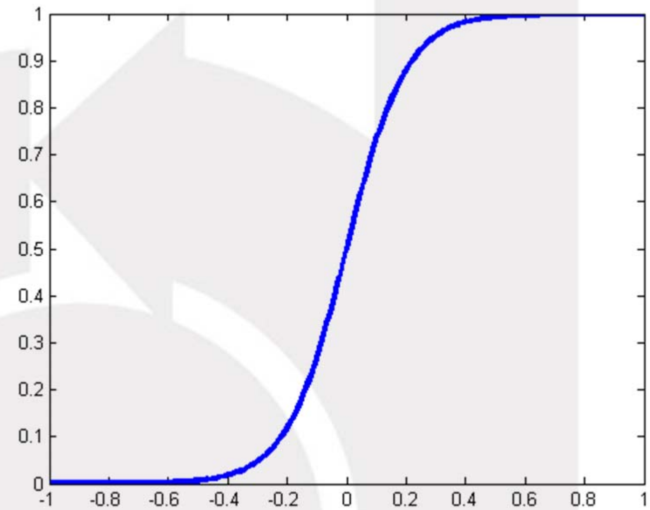


Logistic Function

$$f(x) = \frac{1}{1 + e^{-x}}$$

Introduction to Logistic Regression

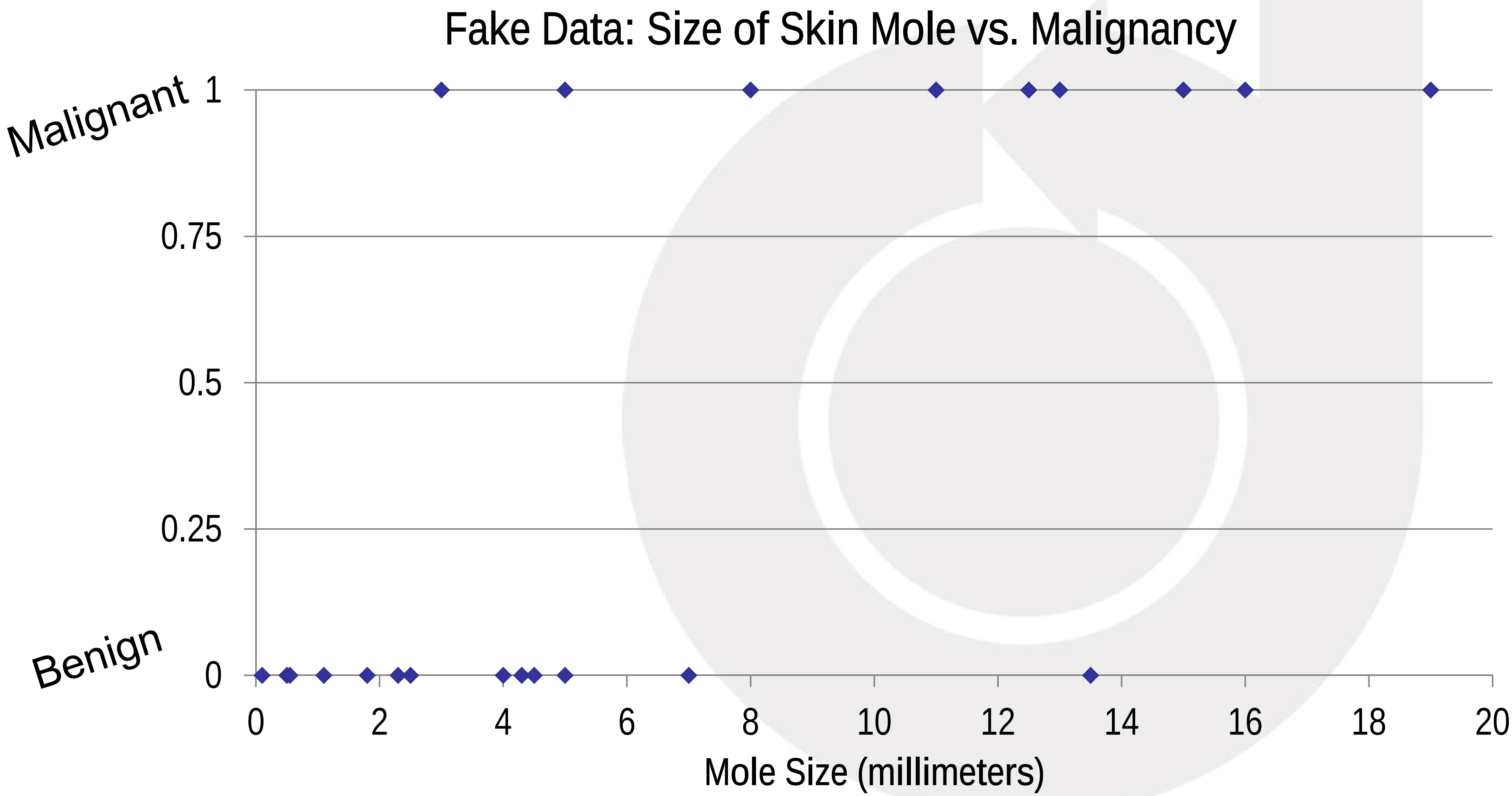
- The value of the logistic function is bounded between 0 and 1.
- Interpret the value of the logistic function to be the probability that the data x is in class $y = 1$.
- Fit a parameter vector θ to the training set to minimize model predictive error.
- Once converged, the model is ready to classify new data.



Hypothesis Function

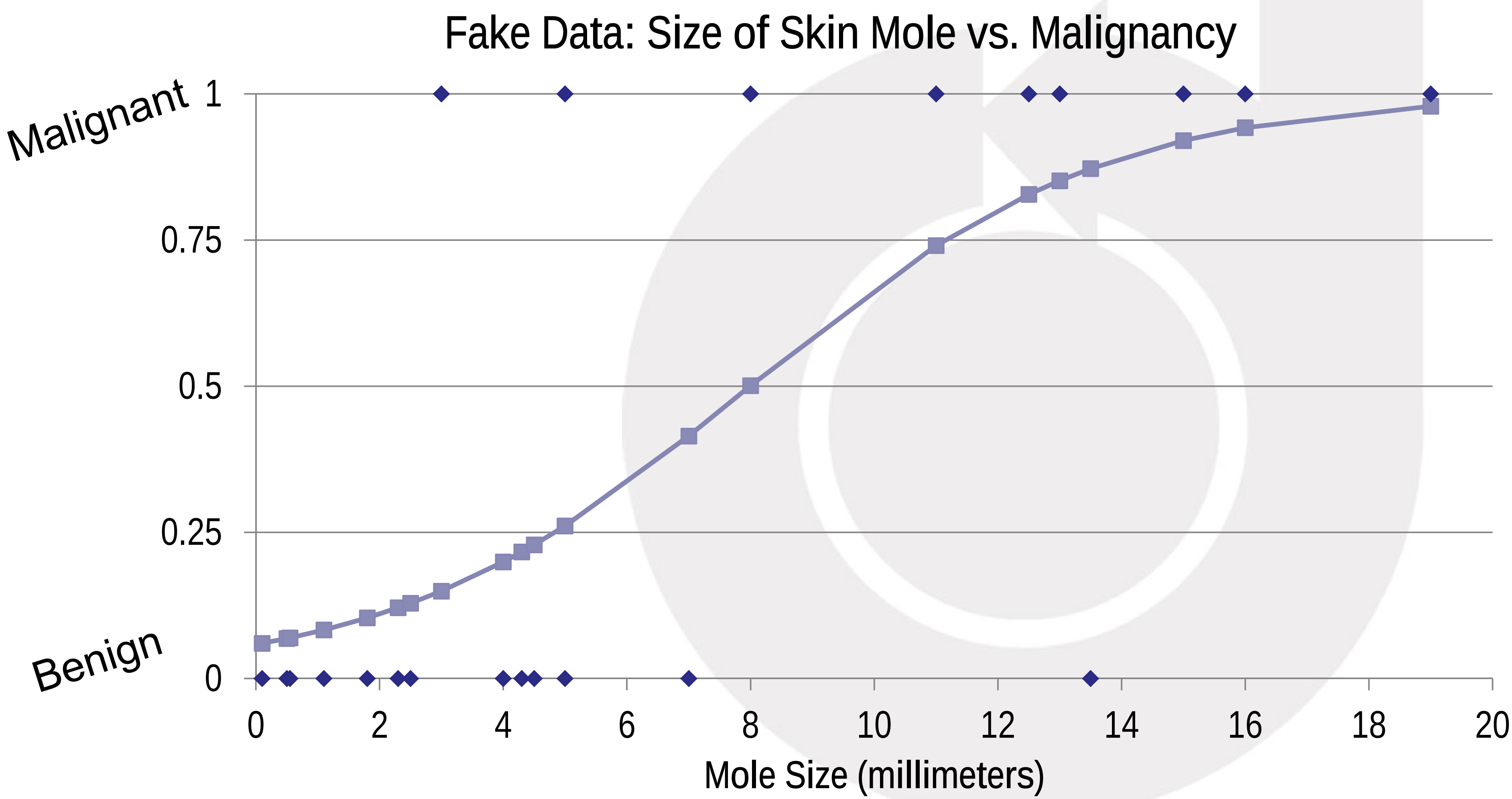
$$P(y|x, \theta) = \frac{1}{1+e^{-\theta^T x}}$$

Logistic Regression Example



Disclaimer: This is not real data. Do not use for medical self-diagnosis.

Logistic Regression Example



Disclaimer: This is not real data. Do not use for medical self-diagnosis.

Applying Logistic Regression to Triggers

- It may be difficult to select a signal to trigger some action in software.
- Logistic regression can aid the designer in determining strong signals for triggers.
- Instead of guessing a trigger signal and tuning a threshold, let an algorithm determine the "best" trigger signals.

Implementation

- Gather training data & labels
  - Training Data: Navigation output from Monte Carlo data
  - Labels:
    - y=1 if truth altitude < 25,000 feet
    - y=0 if truth altitude >= 25,000 feet
- Normalize each dimension of the training data to lie within [-1 1] domain (for numerical reasons).
- Fit a logistic function using gradient descent optimization.
- Once converged, the classifier/trigger is ready for use.

Flight Software Implementation

- Store parameter vector as software parameter.

```
function h = logistic(double[] theta, double[] x) {
      double h = 1 / ( 1 + exp(-transpose(theta)*x) );
      return h;
}

function deploy_command = parachute(PARAM, navStates) {
      double h = logistic(PARAM.THETA, navStates);
      boolean deploy_command = h > PARAM.THRESHOLD;
}
```

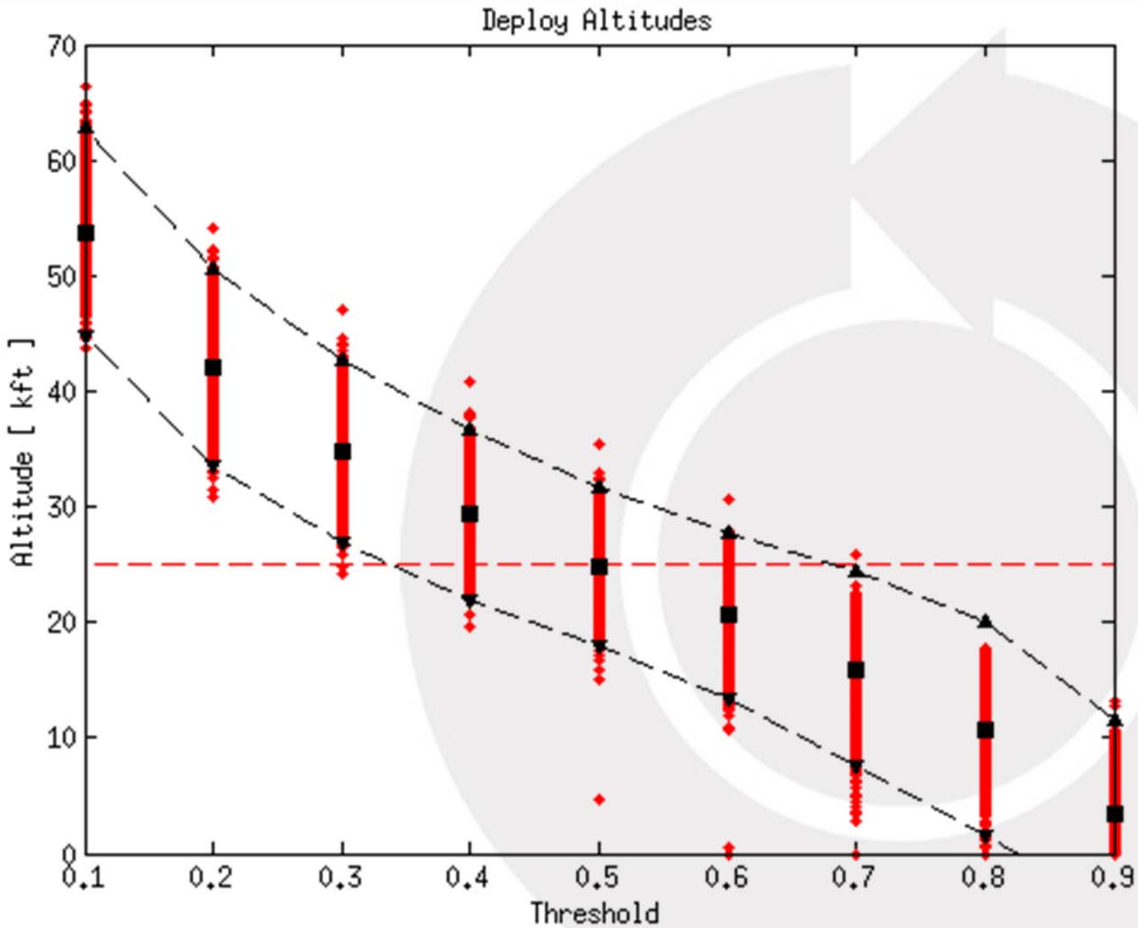
Performance Analysis

- Identify strong signals
- Combine strong signals
  - Multivariate Logistic Regression
- Performance Criteria:
  - Minimize altitude spread at parachute deployment initiation
  - Ensure minimum deployment altitude stays above 25,000 feet.

Results

- Selected Navigation Parameters:
  - Navigated altitude
  - Navigated relative velocity magnitude
  - Elapsed time since sensing 0.2Gs of aerodynamic acceleration
  - Sensed aerodynamic acceleration
  - Navigated Mach number
  - Navigated dynamic pressure
- Record altitude at trigger activation for each trajectory, varying activation thresholds.

Results



Reduced total altitude spread by approximately 3,000 feet as compared to existing approach.

Lessons Learned

- Critical to monitor model fitting process
- May require variable transformations, requiring more designer insight.
- More challenging to understand why a particular trajectory state activated trigger.
- Provides insight into relative value of trigger parameters

Future Work

- Use Naïve Bayes Classifiers to develop triggers
  - Inspired by use in email spam filters
- Preliminary results show large improvements over logistic regression approach.

Conclusion

- Logistic regression is a powerful tool for developing robust flight software triggers.

- Logistic regression can help designer understand the problem space for developing triggers.

The World's Forum for Aerospace Leadership

An Alternative Flight Software Paradigm:

Applying Multivariate Logistic Regression to Sense Trigger Conditions using Inaccurate or Scarce Information

NASA Johnson Space Center
Kelly Smith, Robert Gay, Susan Stachowiak
AIAA GN&C Conference
Boston, August 20, 2013

Introduction

- Orion is scheduled to fly an orbital test flight, Exploration Flight Test-1 (EFT-1), in late 2014
- Mission Profile:
  - Launch from Kennedy Space Center aboard Delta-IV Heavy into LEO parking orbit
  - After 1 orbit, Delta IV-H upper stage injects the vehicle into an elliptical orbit which intersects the Earth
  - Orion separates from upper stage after apogee
  - Orion flies high-speed guided entry, splashes down in Pacific Ocean west of Mexico

Introduction, cont.

- Once high-speed entry is complete, the vehicle must begin a sequence of parachute deployments.
  - Forward Bay Cover (FBC) Jettison
  - Drogue Parachutes
  - Main Parachutes

Motivation

- By design, the parachute deployment sequence (PDS) is to begin no lower than 24,000 feet altitude.
- When GPS is available, navigated altitude errors are small
- If GPS is unavailable, navigation altitude will be informed by backup 3 barometric altimeters (less precise).
- If both GPS and the barometric altimeters are unavailable, then the navigated altitude may have large errors.

Motivation, cont.

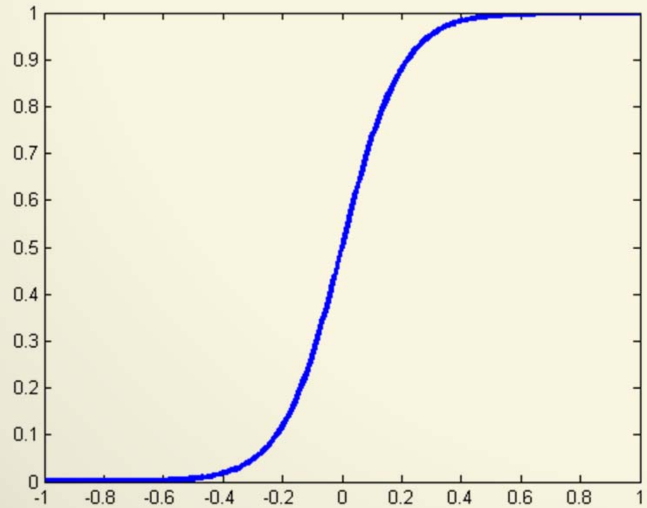
- If navigated altitude contains large errors, the parachute deployment sequence (PDS) will not occur correctly.
- If PDS is still triggered based on navigated altitude in this scenario, many cases impact Earth before PDS.
- An alternative trigger must be developed which uses a less error-prone signal.

Flight Software Triggers

- Typically, triggers are normally simple checks against thresholds:
  - `if (altitude <= 24000) { deploy_parachute(); }`
- When required, additional conditions are added to increase the specificity of the trigger:
  - `if (altitude <= 24000 && gps_is_available == true) { deploy_parachute(); }`
- When adding new conditions, the number of additional code paths increases, increasing code complexity.
- Code complexity increases software testing costs.
- Therefore, to minimize costs, simple flight software triggers are desired.

Introduction to Logistic Regression

- A statistical technique used for fitting a curve to classify data into separate classes.
- Simplest version is binary logistic regression (2 classes of data)
- Fit a logistic function, also known as a sigmoid function (S-curve), to these two classes of data

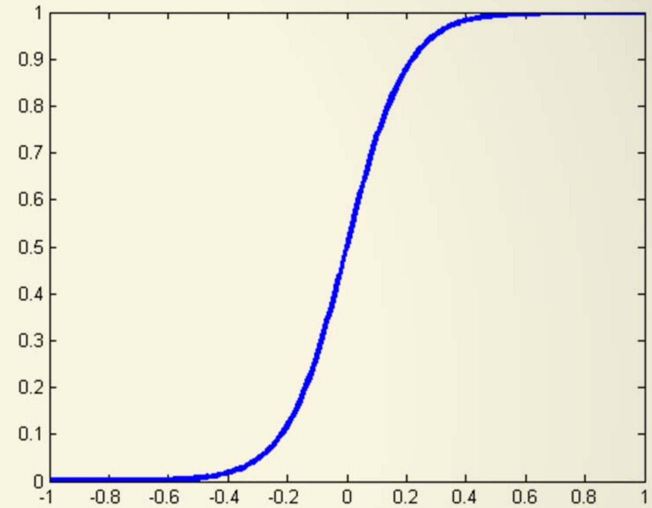


Logistic Function

$$f(x) = \frac{1}{1 + e^{-x}}$$

Introduction to Logistic Regression

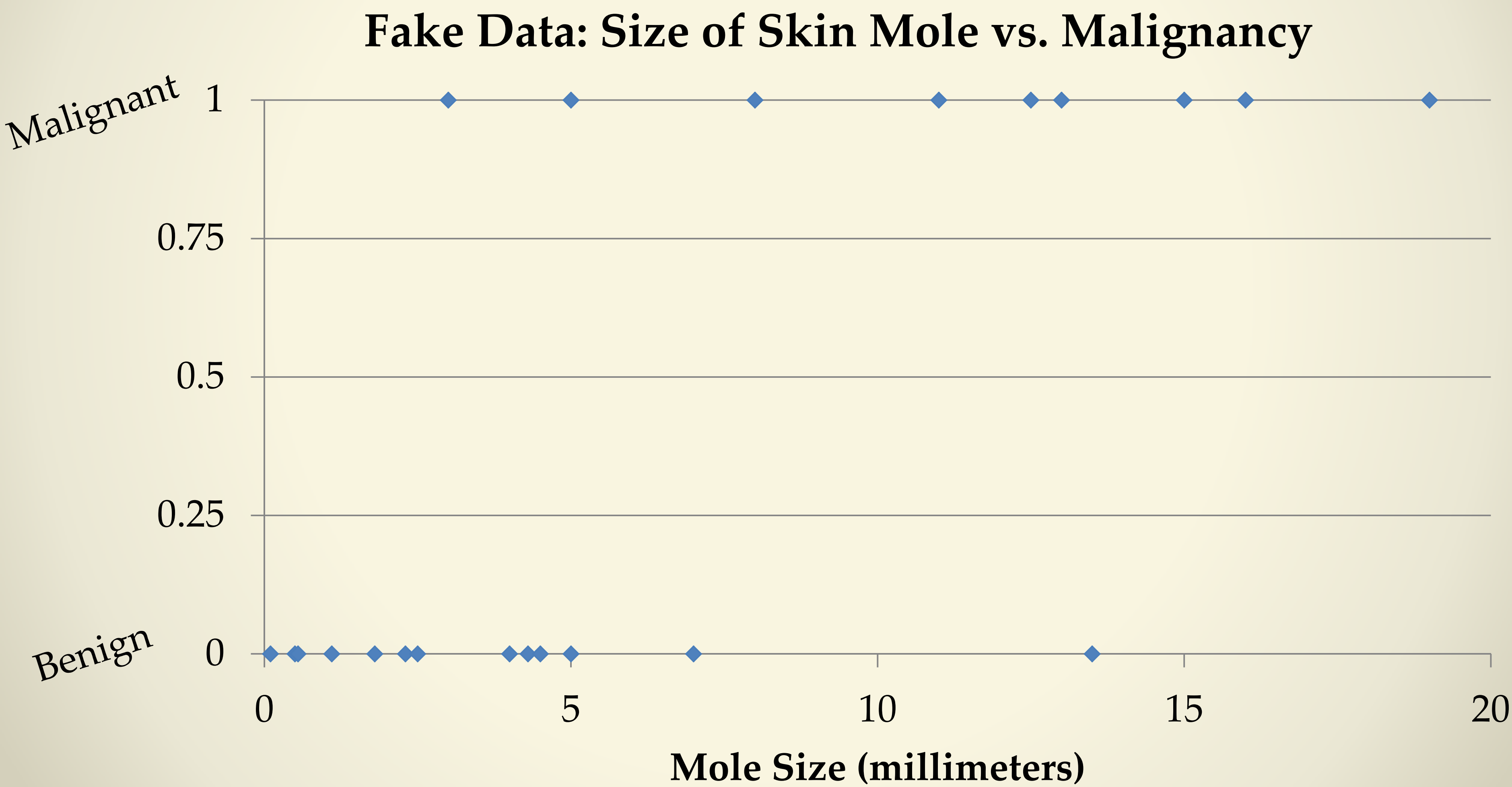
- The value of the logistic function is bounded between 0 and 1.
- Interpret the value of the logistic function to be the probability that the data x is in class $y = 1$.
- Fit a parameter vector θ to the training set to minimize model predictive error.
- Once converged, the model is ready to classify new data.



Hypothesis Function

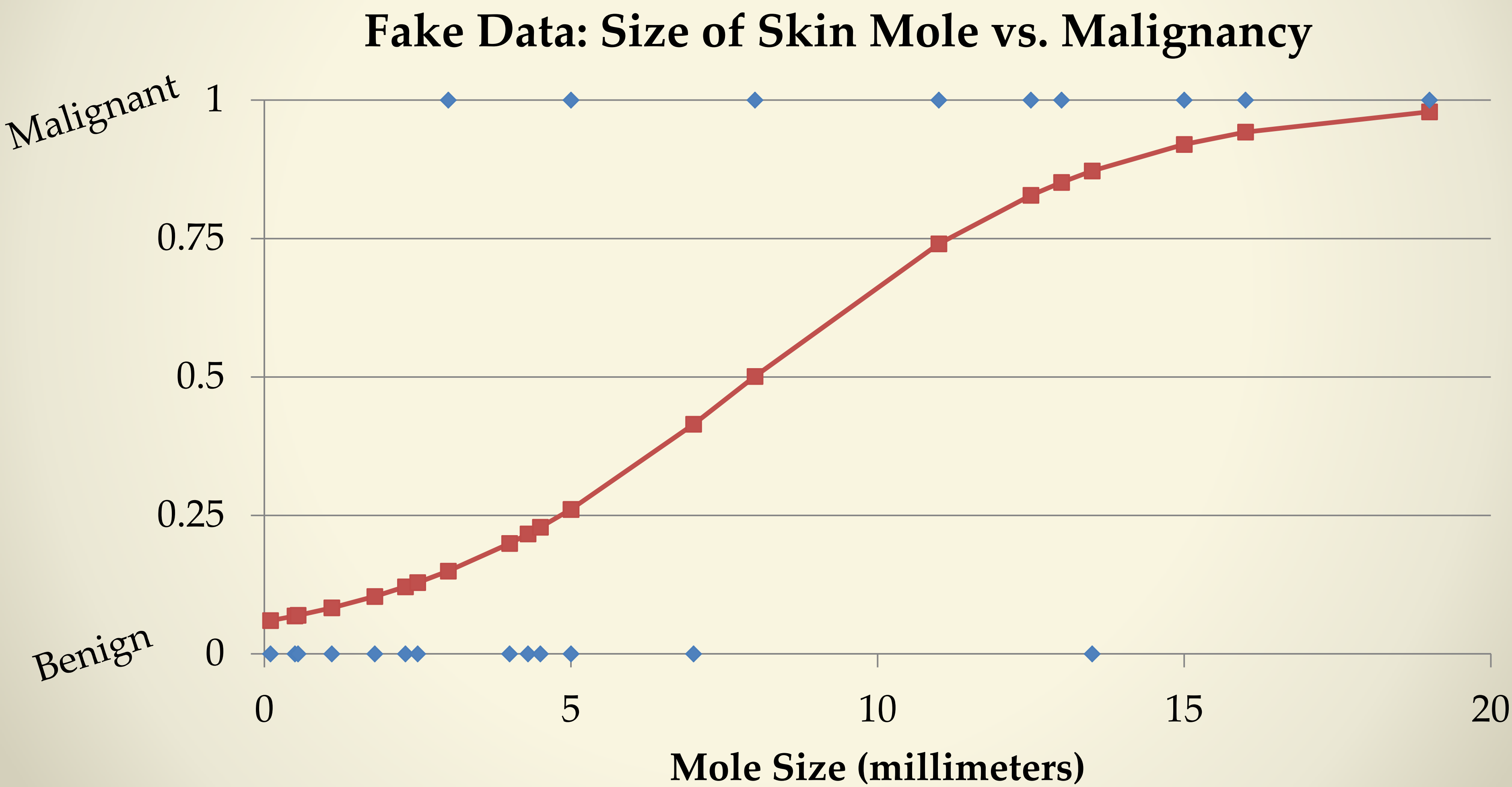
$$P(y|x,\theta) = \frac{1}{1+e^{-\theta^T x}}$$

Logistic Regression Example



- Disclaimer: This is not real data. Do not use for medical self-diagnosis.

Logistic Regression Example



- Disclaimer: This is not real data. Do not use for medical self-diagnosis.

Applying Logistic Regression to Triggers

- It may be difficult to select a signal to trigger some action in software.
- Logistic regression can aid the designer in determining strong signals for triggers.
- Instead of guessing a trigger signal and tuning a threshold, let an algorithm determine the “best” trigger signals.

Implementation

- Gather training data & labels
  - Training Data: Navigation output from Monte Carlo data
  - Labels:
    - y=1 if truth altitude < 25,000 feet
    - y=0 if truth altitude >= 25,000 feet
- Normalize each dimension of the training data to lie within [-1 1] domain (for numerical reasons).
- Fit a logistic function using gradient descent optimization.
- Once converged, the classifier/trigger is ready for use.

Flight Software Implementation

- Store parameter vector as software parameter.
- Flight software should contain some function to evaluate logistic function:

```
function h = logistic(double[] theta, double[] x) {
      double h = 1 / ( 1 + exp(-transpose(theta)*x) );
      return h;
}

function deploy_command = parachute(PARAM, navStates) {
      double h = logistic(PARAM.THETA, navStates);
      boolean deploy_command = h > PARAM.THRESHOLD;
}
```

Performance Analysis

- Identify strong signals

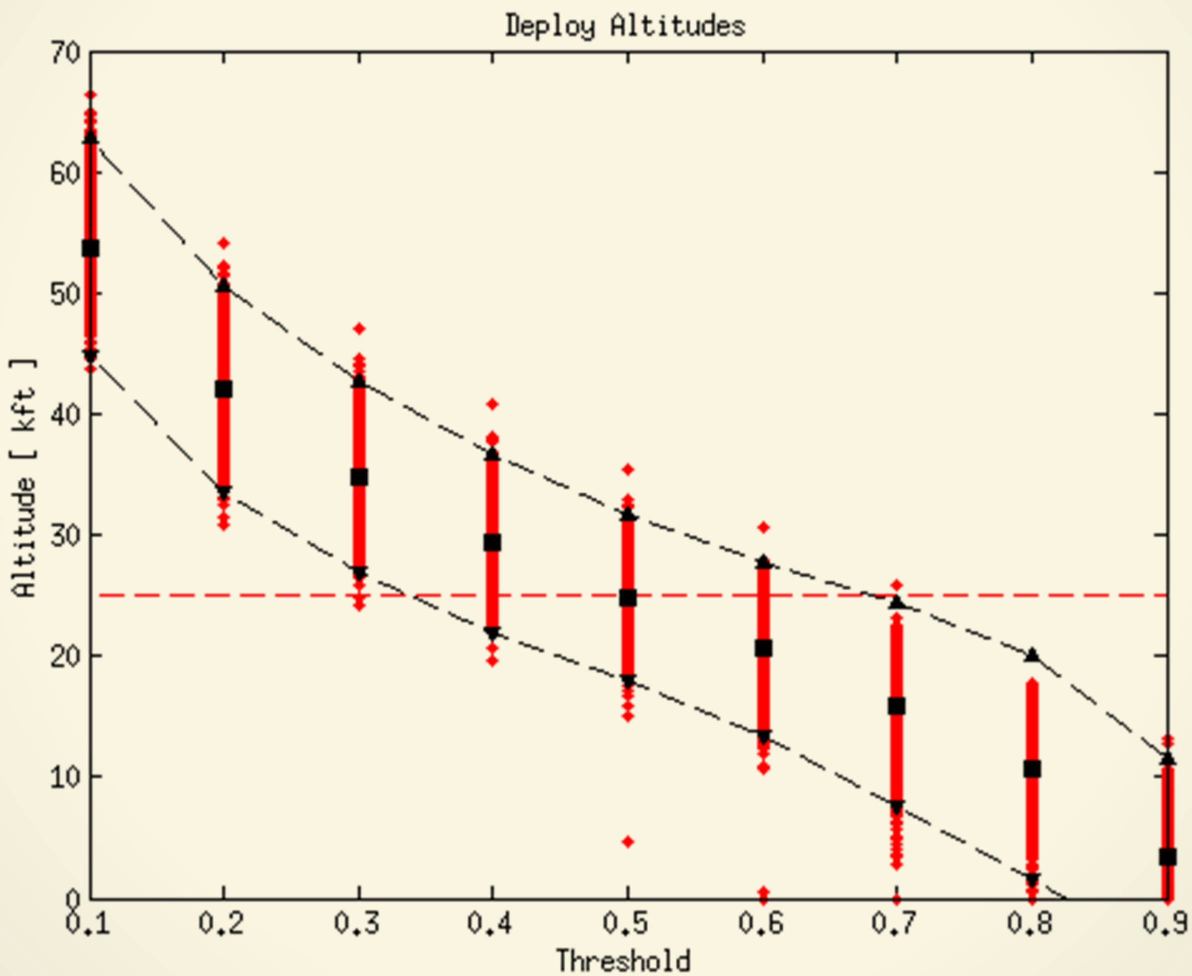
- Combine strong signals
  - Multivariate Logistic Regression

- Performance Criteria:
  - Minimize altitude spread at parachute deployment initiation
  - Ensure minimum deployment altitude stays above 25,000 feet.

Results

- **Selected Navigation Parameters:**
  - Navigated altitude
  - Navigated relative velocity magnitude
  - Elapsed time since sensing 0.2Gs of aerodynamic acceleration
  - Sensed aerodynamic acceleration
  - Navigated Mach number
  - Navigated dynamic pressure
- Record altitude when trigger is first activated for each trajectory for a range of trigger activation thresholds.

Results



Reduced total altitude spread by approximately 3,000 feet as compared to existing approach.

Lessons Learned

- Critical to monitor model fitting process
- May require variable transformations, requiring more designer insight.
- More challenging to understand why a particular trajectory state activated trigger.
- Provides insight into relative value of trigger parameters

Future Work

- Use Naïve Bayes Classifiers to develop triggers
  - Inspired by use in email spam filters
- Preliminary results show large improvements over logistic regression approach.

Conclusion

- Logistic regression is a powerful tool for developing robust flight software triggers.
- Logistic regression can help designer understand the problem space for developing triggers.